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Resonant frequency dependence on outer diameter of high Tc rf-SQUID

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Abstract

Superconducting quantum interference devices (SQUIDs) have been applied to various magnetic sensing. An rf-SQUID can measure magnetic signals by applying external rf-magnetic field whose frequency is tuned to its resonance. Our rf-SQUID having the outer diameter of 3.5 mm needed a substrate resonator to operate it within the operation frequency range of our using FLL electronics. The designs of the rf-SQUID and the resonator were critical to the resonant frequency and the effective area. In this paper, the outer diameter dependence of the resonant frequency and the effective area were investigated by both the electromagnetic simulations and the experiments. The results showed that the rf-SQUID having the larger outer diameter has the smaller resonant frequency and the larger effective area. The rf-SQUIDs having the larger outer diameter were fabricated according to the simulation results. They could be operated within the operation frequency range even though a resonator was omitted.

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Keywords: rf- SQUIDs; radio frequency; resonant frequency; effective area; outer diameter

1. Introduction

Superconducting quantum interference devices (SQUIDs) have been investigated for various magnetic sensing applications. One of the important applications is the magnetic microscope. We have developed an STM-SQUID microscope, in which an rf-SQUID is combined with a scanning tunneling microscope by using a probe with a sharp tip made of permalloy[1]. The magnetic domain structures were successfully observed in a resolution value of 100 nm. However, the flux transferred from the sample to the SQUID through the probe was decreased by a factor of more than 1,000. The critical flux drop was found between the SQUID and the probe. Because the gap distance between the probe and the SQUID affected the quality of the magnetic images, it was necessary to decrease the gap distance.

In general, an rf-SQUID is used with a magnetically coupled resonator. The rf-SQUID can detect a magnetic field while applying the rf-magnetic field whose frequency was adjusted to the resonance. The resonant frequency and the effective area depend on the designs of the rf-SQUID and the resonator. Our rf-SQUID having the outer diameter of 3.5 mm also needed the substrate resonator to operate because the resonant frequency of the rf-SQUID without using a resonator was about 1,100 MHz, which was out of the range of the flux locked loop (FLL) electronics (HTSL-RF-SQUID-ELEKTRONIK ver.5, Jülicher SQUID GmbH) we are using. If the substrate resonator is omitted, it will be easy to decrease the gap distance between the SQUID and the probe in our microscope. Chen *et al*. showed that the resonant

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frequency depended on the design of a substrate resonator, which was placed on the rf-SQUID in a flip-chip configuration, as shown in Fig. 1(a) [2]. In addition, some groups reported the integrated rf-SQUIDs, in which the rf-SQUID and the substrate resonator patterns were combined into one design, to operate the rf-SQUID without using a resonator [3, 4]. From these reports, it was expected that the resonant frequency of an rf-SQUID used with a resonator should depend on the total shape of their superconducting films, and therefore that the outer diameter of the rf-SQUID could strongly affect the resonant frequency. In this study, firstly the resonant frequency in flip-chip configuration using the washer-type substrate resonator was investigated by changing the outer diameter of the resonators. Then, the dependence of the resonant frequency on the outer diameter of rf-SQUIDs was investigated without using a resonator. The rf-SQUID without using substrate resonator will be beneficial for the STM-SQUID microscope.

2. Designs of rf-SQUID and substrate resonator

The rf-SQUID was made of $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin film (thickness: 120 nm) deposited on a 1 cm square $SrTiO_3$ (STO) bicrystal substrate (thickness: 0.5 mm). The rf-SQUID washer pattern was fabricated having the outer diameter of 3.5 mm. The SQUID hole size, the slit and Josephson junction width of the SQUID were 100×100 µm^2, 10 µm and 5 µm, respectively, as shown in Fig. 1(b). The substrate resonator was also fabricated on a 1 cm square single crystal substrate (thickness: 0.5 mm). The resonator pattern was 9 mm square YBCO film with a keyhole shape, as shown in Fig. 1(c). In the simulations, the S11 calculations were carried out to determine the resonant frequencies by a method of moment electromagnetic simulator (FEKO, EM Software & Systems). The YBCO films were also modeled as perfect conductors. In the experiments, the rf-SQUIDs and resonators were fabricated with the same designs as the simulation models. Their characteristics were measured at liquid nitrogen temperature.

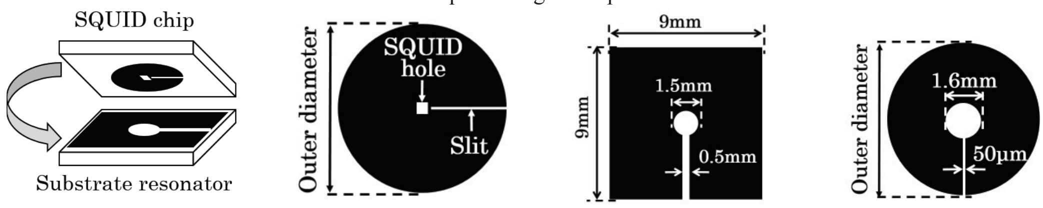

Fig.1 (a) Schematics of the flip-chip configuration. (b) Designs of the rf-SQUID, and (c) the substrate resonator. (d) design of the circle type substrate resonator.

3. Resonant frequency of rf-SQUID using substrate resonator

Fig. 2(a) shows the reflectance (S11) of the rf-SQUID (outer diameter: 3.5 mm) as the function of the excited frequency when the rf-SQUID was used with and without using the substrate resonator (Fig. 1(c)) in a flip-chip configuration, measured by a network analyzer from the coupled single turn coil. When the rf-SQUID was operated without using a resonator, the resonant frequency was about 1,100 MHz. On the other hand, when the rf-SQUID was operated with using the resonator, the resonant frequency was changed to about 650 MHz, and the Q factor was also increased a high enough to excite the rf-SQUID. Fig. 2(b) shows the resonant frequency dependence on the outer diameter of circle type resonators (Fig. 1(d)), set in a flip-chip configuration obtained by the electromagnetic simulation

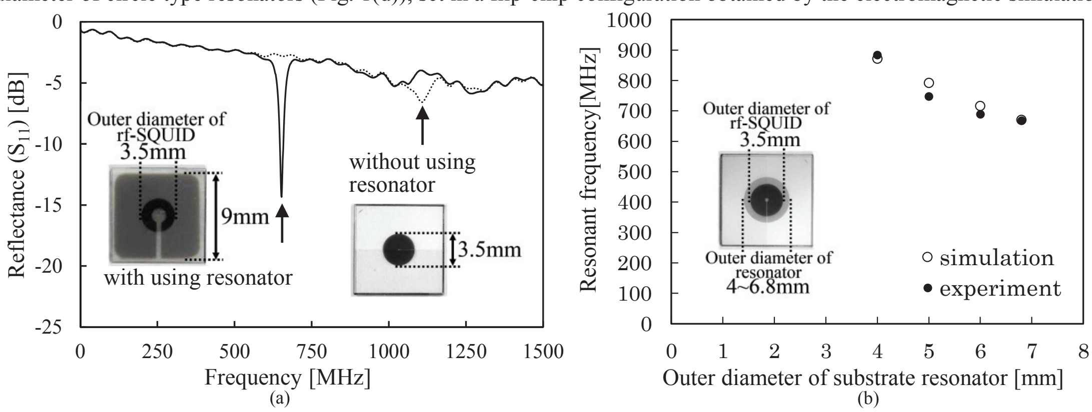

Fig. 2. (a) Reflectance spectrum of the rf-SQUID having the outer diameter of 3.5 mm with and without using a resonator. The dotted lines show the results obtained without using a resonator, whereas the solid line shows the result with using the resonator. (b) Resonant frequencies of the same rf-SQUID (outer diameter: 3.5 mm) with using the circle type substrate resonators, of which outer diameters were changed from 4 to 6.8 mm.

and the experiment. The outer diameter of the resonators was changed from 4 to 6.8 mm. The simulation results were plotted as the opened circles, and the experiment ones were plotted as the closed circles. The experiment results are in good agreement with the simulation results. It indicated that the outer diameter of the resonator is related with the resonant frequency of the rf-SQUID. The resonant frequency was changed from 884 to 668 MHz with increasing the outer diameter of the resonator from 4 to 6.8 mm. When the resonator with the lager diameter was used, the resonance of the rf-SQUID showed the lower frequency.

4. Resonant frequency of rf-SQUID without using the substrate resonator

The result of the flip-chip configuration using the rf-SQUID and the resonator indicates that the rf-SQUID will be operated without using a resonator if the outer diameter of rf-SQUID is relatively large. The resonant frequencies of the rf-SQUIDs having different outer diameters changed from 2 to 9 mm without using a resonator were calculated to determine the outer diameter of the rf-SQUID in advance of the experiment. The SQUID hole size and the slit width were the same as for the initial one, as shown in Fig. 1(b). Fig. 3(a) shows the simulation result, plotted as the opened circles. It indicates that the resonant frequency can be decreased by increasing the outer diameter of the SQUID, similarly to the result of the flip-chip configuration. The rf-SQUIDs having the outer diameter of 3.5, 4, 5, 6, and 7 mm were actually fabricated with the same designs as the simulation models. Fig. 3(b) shows the reflectance spectrum measured for the rf-SQUID having the outer diameter of 7 mm without using a resonator. The resonant frequency of the rf-SQUID was decreased to 650 MHz though that of the rf-SQUID having the diameter of 3.5 mm was 1,100 MHz. In addition, the rf-SQUID had high enough Q value to operate it without using a resonator. The resonant frequencies of the rf-SQUIDs having different diameters were also plotted as the closed circles in the Fig. 3(a). The experiment results are also in good agreement with the simulation ones. The rf-SQUIDs having the outer diameter of 5, 6, and 7 mm, whose resonant frequencies were within frequency range of the FLL electronics, could be operated without using a resonator.

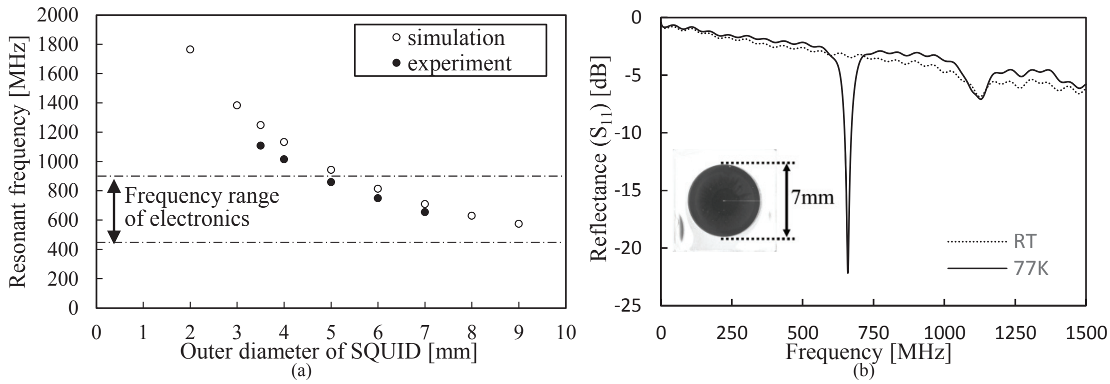

Fig. 3. (a) Resonant frequency of the rf-SQUID without using a resonator as the function of the outer diameter of the rf-SQUID. The arrow shows the frequency range of our using FLL electronics. (b) Reflectance spectrum of the rf-SQUID having the outer diameter of 7 mm, obtained without using a resonator. From the comparison between the spectra measured at room and liquid nitrogen temperature, the resonant frequency corresponding to the rf-SQUID can be determined. The inset photograph shows the measured rf-SQUID.

5. Effective area of rf-SQUID

The dependence of the effective area on the outer diameter of the rf-SQUID was also investigated by both the electromagnetic simulation and the experiment. The simulation was carried out by a static field simulator using finite element method (Modeler: Opera-3D, Solver: TOSCA magnetic). The effective area corresponds to the area, as shown in Fig. 4(a). It can be calculated from $\Phi_{\mathrm{in}}/\Phi_{\mathrm{field}}\times A_{\mathrm{hole}}$, where A_{hole} is the area of the SQUID hole, Φ_{in} is the magnetic flux obtained inside A_{hole} with the rf-SQUID, and Φ_{field} is the flux obtained inside the same area as A_{hole} only from solenoidal coil without the rf-SQUID. In the simulation model, the SQUID was modeled washer having only the hole (the slit was omitted) for the easy calculation. The hole size was defined as the same size of $110 \times 110\ \mu\mathrm{m}^2$ as the actual rf-SQUIDs, which was a little bit larger than that of the original design due to the side etching in the fabrication process. The relative permeability of the SQUID was set at 10^{-4} (the minimum value in the simulator). The outer diameter of the SQUID model was changed from 2 to 9 mm. The SQUID was placed at the center of solenoidal coil. The effective areas obtained from the simulation were plotted as the opened circles in the Fig. 4(b).

In the experiments, the effective areas were measured for the rf-SQUID (3.5 mmϕ) with using the substrate resonator and for the rf-SQUIDs having different outer diameters changed from 5 to 7 mm without using the resonator. The results of the rf-SQUIDs with and without using the resonator were plotted as the double circle and the closed circles, respectively. Both the experiment and the simulation results indicate that the effective area of the rf-SQUID is increased along with increasing the outer diameter of the rf-SQUID.

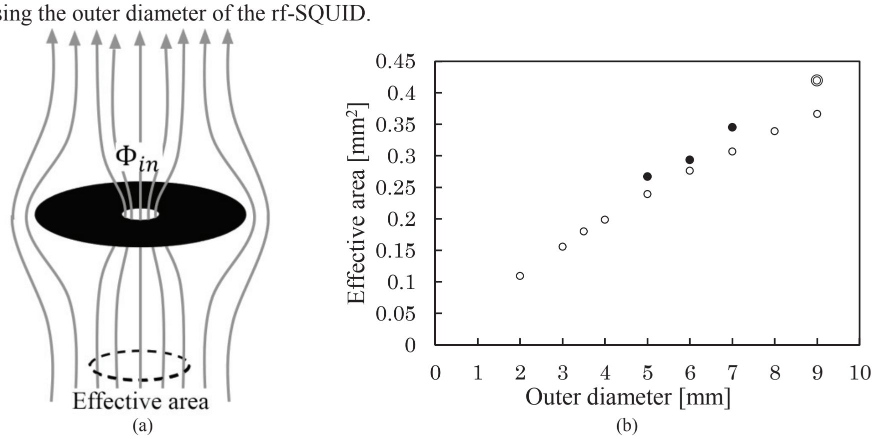

Fig. 4. (a) Schematics of the effective area of the rf-SQUID. (b) Effective areas of the rf-SQUIDs with and without using the resonator as the function of the outer diameter of the rf-SQUID. The diameter for the rf-SQUID with using the resonator was defined as the width of the resonator.

6. Noise comparison of rf-SQUIDs

Fig. 5(a) and (b) show the noise density spectrum of the rf-SQUID having the outer diameter of 3.5 mm using the substrate resonator (the same device in Fig. 2(a)) together, and that of the rf-SQUID having the outer diameter of 7 mm without using the resonator (the same device in Fig. 3(b)). The positional relationship among the rf-SQUID, the substrate resonator and the readout coil is shown in the each inset of Fig. 5. The white noise level in Fig. 5(b) is very similar to Fig. 5(a), even though the substrate resonator was omitted. The rf-SQUID having the outer diameter of 7 mm could show almost the same performance as the rf-SQUID (3.5 mmϕ) used with using the substrate resonator.

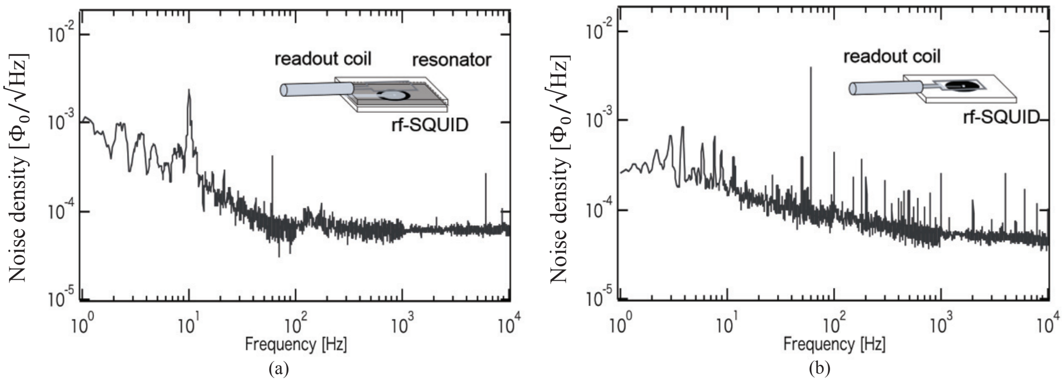

Fig. 5. (a) Noise density spectrum of the rf-SQUID having the outer diameter of 3.5 mm with using the substrate resonator, and (b) having the outer diameter of 7 mm without using a substrate resonator.

7. Conclusion

The dependence of the resonant frequency on the outer diameter of the substrate resonator or the rf-SQUID was investigated by both the electromagnetic simulations and the experiments. The simulation results are in good agreement with the experiments. The results indicated that the substrate resonator is not essential to operate to the rf-SQUID, and that the rf-SQUID having the larger diameter can be excited and operated without using a resonator. For example, a newly fabricated rf-SQUID having the outer diameter of 7 mm had a high enough Q value to operate without using the substrate resonator. Moreover, the noise performance of the newly fabricated rf-SQUID without using a resonator was similar to the rf-SQUID having the outer diameter of 3.5 mm with using the substrate resonator.

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